Chapter 6
Location and Design of Test Quarries

6-1. General

The final location, physical size, and design of a test quarry is made using the information obtained during the reconnaissance, site selection, and initial and design investigations. The development of the test quarry program and the test quarry design is an iterative process. Preliminary requirements for and locations of test quarries are developed during the reconnaissance phase of project development and refined sufficiently during the feasibility phase to provide accurate data for baseline cost estimates and for proceeding to detailed design during the preconstruction engineering design phase. The process of locating and designing the project test quarry, or test quarries, follows a logical sequence as described in the following paragraphs.

6-2. Evaluation of Project Rock Production Requirements

Concurrent with the investigations required to locate and design a test quarry are those required to determine embankment design, including zoning and slope protection requirements. The need for rock-fill zones in an embankment arises from the overall analyses of the amounts of different types of fill materials available and the results of cost studies of various embankment cross sections and alignments. The decision to design and construct a rock-fill embankment is made based on design safety considerations and on analyzing the comparative costs among rock, earth-rock, and earth embankments and concrete structures. Guidelines on the procedures for selecting the safest and most economical design are contained in EM 1110-2-2300. As the embankment design develops, volumes for different qualities and gradations of rockfill are determined. These are compared with the probable amounts of rock of those qualities and gradations that design investigations indicate are available in required excavations or in separate excavations specifically planned to supply rock material. This process is iterated until the most economical balance between excavation and fill requirements is obtained which will produce a safe embankment. The supply of rock reserves available for construction of the dam must be accurately estimated, taking into account bulking and/or shrinkage factors. These quantity estimates can be greatly improved if bulking and shrinkage factors are determined during test quarry and test fill development.

6-3. Evaluation of Potential Test Quarry Sites

At this stage in the design process, required excavation and/or stand-alone quarry sites have been explored as potential sources of construction materials. It remains to evaluate these sites and decide upon one or more test quarry locations which will provide data that are most representative of the conditions to be encountered in the project excavation(s). The quarry or quarries should be sited so that all large-volume rock types to be used in construction and all associated rock conditions will be assessed and tested. If the amount of a particular rock type will be relatively small and failure to assess it will result in errors of minor technical and economic consequences during construction, the time and cost of developing a test quarry only to assess it may not be justified.

a. Rock type distribution considerations. The test quarry, or quarries, should sample the same rock types, in roughly the same proportionate quantities, that will be provided from the actual project excavation(s). A project may be located in one rock or several depending on the areal geologic sequence (sedimentary, igneous, metamorphic). The degree of heterogeneity will control the number and location of test quarries. In a relatively homogeneous igneous or metamorphic crystalline rock, one test quarry of sufficient size to sample the unweathered rock may suffice. In a bedded sedimentary sequence, a large spillway excavation may be planned to cut across several rock types. Ideally, the test quarry should be of sufficient size that it will sample this heterogeneity and supply adequate materials for test fills. However, monies available at this stage may not allow a test quarry of that size. A number of smaller test quarries may provide a representative blend of materials for test fills and provide representative information on rock gradations, waste and slope design. However, great care must be used in modeling of the rock conditions to be produced from one large excavation with a number of smaller excavations. As will be pointed out in paragraph 7-2*b*, there are potential problems involved in not siting the test quarry within the area of the intended project borrow excavation.

b. Geologic structure and fabric considerations. Test quarries should not be located so that they include gross or meso-scale geologic structural features such as faults and solution cavities. Macro-scale geologic structure, such as joints and bedding planes, affects both the gradation of the blasted rock mass and the stability of the quarry slopes. The regional residual stress field will have an effect on quarry slope stability and on rock

fragmentation. The effect of the geologic structure on the design of the quarry slopes will be discussed below in paragraph 6-3*d* and its effect on the blasted rock mass gradation will be discussed in paragraph 6-3*c*. Geologic fabric, or arrangement of the rock's mineral constituents, affects both the ease with which comminution occurs under the dynamic loads of explosives and the shape of the blasted rock fragments. The test quarry, or quarries, should be sized and located so that all the variations of geologic structure which will be encountered in the project quarry excavations will be sampled. Generally, an adequate sampling of rock fabric is obtained if the test quarry, or quarries, adequately sample all the rock types to be encountered in the project construction situation.

c. Rock quality and gradation considerations. As with rock type, geologic structural and fabric considerations, the number and size of test quarries should be selected so that the variations in rock quality over the planned construction quarry excavations are sampled. If, as recommended in paragraph 4-4*b*, sufficient data were collected during subsurface investigations to employ the use of a rock-mass classification system, the rock mass in the required excavations can be divided into zones of different rock mass qualities and that zoning can assist in the location of the test quarries. The in situ rock block-size distribution will have a great deal of influence on the gradation of the blasted rock. The degree of variation of in situ block-size distribution can be established from the logs of exploration core borings. There are two ways to assess this degree of variation. Mean block-size distribution for pre-selected lengths of each bore hole can be estimated from *RQD* using the following relationship (Brady and Brown 1985).

$$RQD = 100\, e^{-0.1\lambda}\,(0.1\lambda + 1) \qquad (6\text{-}4)$$

where e is the exponential and λ is the mean number of discontinuities per meter. Figure 6-1 shows the relationship between *RQD* and mean discontinuity frequency. A more site-specific and accurate method of estimating the in situ block-size distribution is to make cumulative fracture frequency curves from the fracture counts on the boring logs and/or from borehole photography logs. This will allow the division of the rock mass by the mean fracture spacing and variance in a manner similar to zoning the rock mass according to rock mass quality.

d. Rock slope design considerations. Because the test quarries will provide the opportunity to test the project excavation slope designs, the test quarry excavation(s) should be configured to duplicate project slope inclinations and orientations. As part of the test quarry location and sizing analyses, slope stability evaluations should be employed for trial quarry configurations. Preliminary evaluations of slope stability can be performed with graphical analyses using stereographic or equal-area projections. An example of such an evaluation is shown in Figure 6-2. If preliminary evaluations indicate potential instabilities, more detailed planar and wedge stability analyses should be performed. An excellent series of discussions on rock slope stability analyses is presented by Hoek and Bray (1981). There should be sufficient slope area to test all potential presplit configurations.

6-4. Test Quarry Layouts

Test quarries should be located, if feasible, within the perimeter of the area to be used as the primary source of rock for project construction. Reasons for this will be discussed in paragraph 7-2*b*. As stated in paragraph 6-3, the quarry, or quarries, should be located so that all major rock types and rock conditions can be tested and evaluated. It is presumed that, before final selection of the test quarry site(s), sufficient core borings will have been drilled in each potential quarry location to determine if the desired rock type and rock conditions will be encountered in the selected test quarry(ies). The layout of each quarry must take into consideration the slope of the terrain, the depth of overburden and saprolite, the configuration of the objective strata, and accessibility to the test fill site. Cost of the test quarry is always a consideration; the location and layout must achieve reasonable economy. Figures 6-3 through 6-6 are examples of single-test and multiple-test quarry layouts, respectively.

a. Stripping requirements. It is necessary to strip all of the overburden and saprolite and haul it to a disposal site prior to initiation of rock excavation in the test quarry. This is important because the rock fill produced in the test quarry should not be contaminated by the overlying materials. It is advisable to create a berm or bench on the order of 3 to 7 m (10 to 20 ft) wide between the base of the slope through overburden and the beginning of the first rock excavation slope. This should be done to control surface drainage and raveling of overburden into the quarry during the continuing excavation.

b. Size and alignment. The size of the test quarry is dictated by a number of different factors. Depth to the target rock formation, quantity of material required for test fills, geologic structure and side slopes, variations in rock types and rock quality, and the number of test blasts needed are all factors which must be considered in

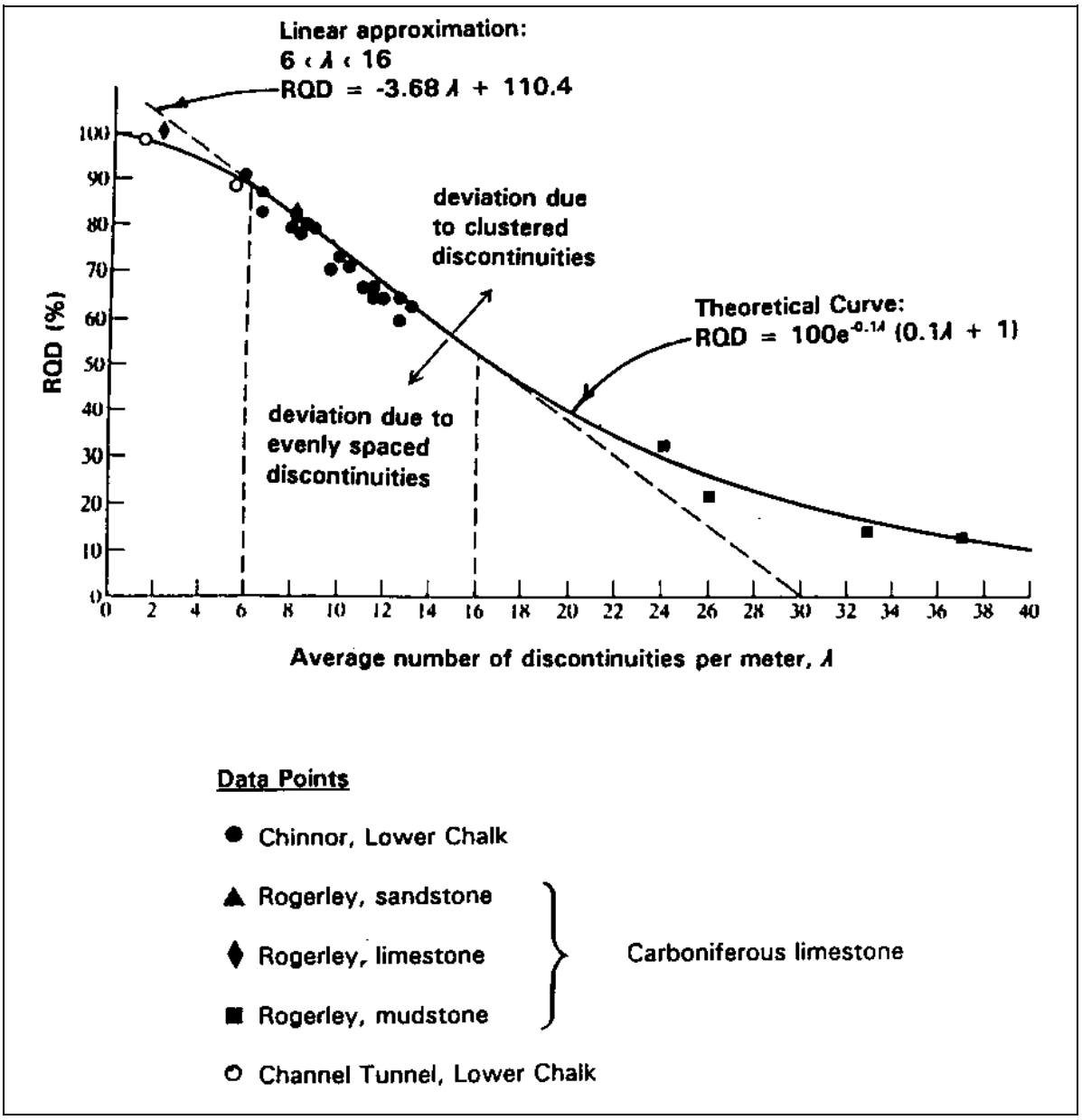


Figure 6-1. Relationship between *RQD* and mean discontinuity frequency (after Brady and Brown 1985)

designing the dimensions of the test quarry(ies). It is important to plan the size of the excavation larger than the minimum required in case it becomes necessary to excavate the quarry deeper than the design depth. Extending an exact-sized quarry to greater depth would require re-excavating the slopes in order to maintain their stability. This may become prohibitively expensive. The alignment of the excavation is affected by some of the factors that affect its size but terrain configuration frequently controls the alignment. An example of terrain-controlled alignment is shown in Figures 6-3 through 6-5.

c. Slope and bench designs. Slope design should be based upon rock slope stability analyses employing rock fracture orientations developed from the geologic investigations and rock shear strengths developed from the results of laboratory testing. One purpose of the test quarry is to field test the slope design. For this reason,

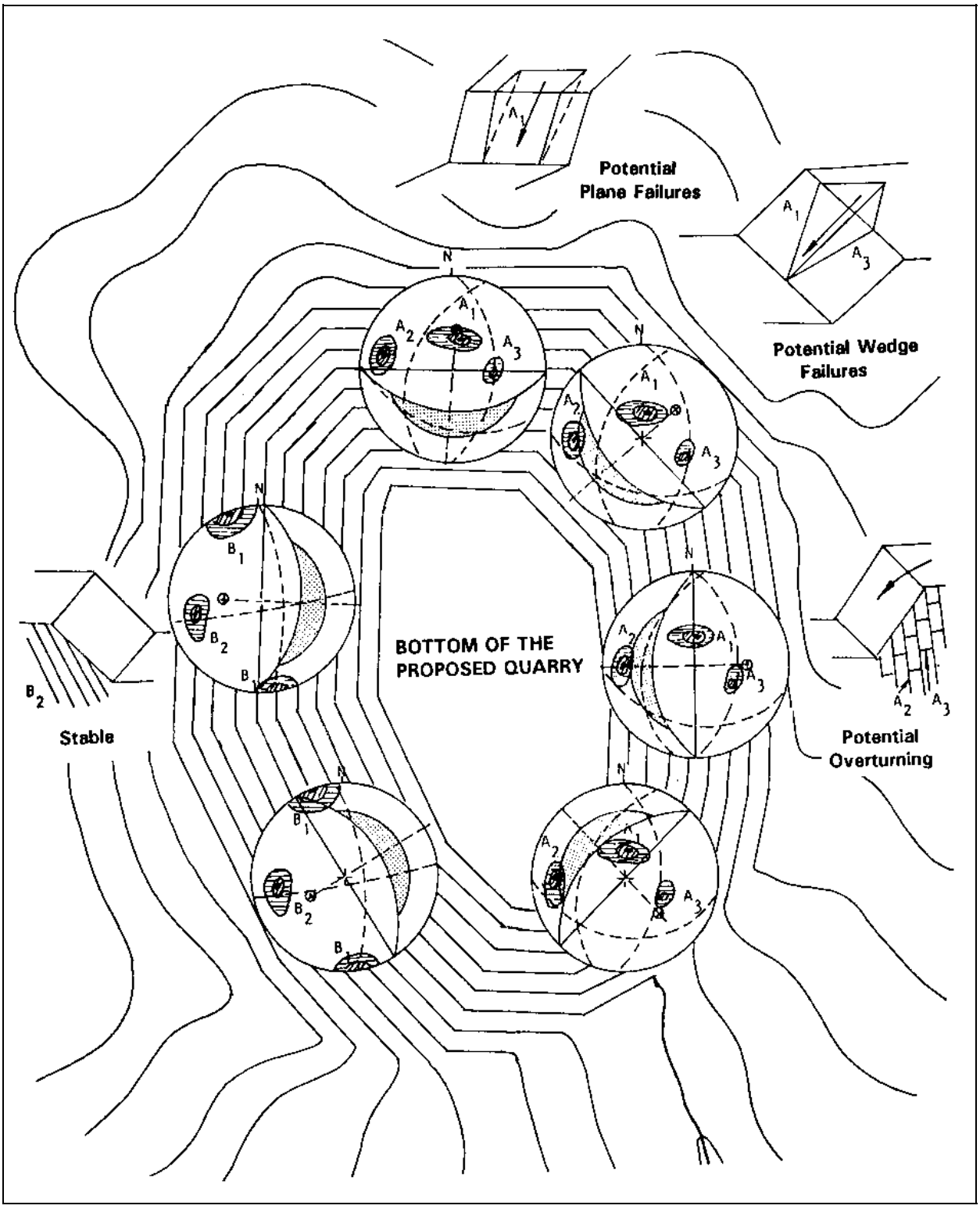


Figure 6-2. Example of a graphical slope stability evaluation of a proposed excavation (after Hoek and Bray 1981)

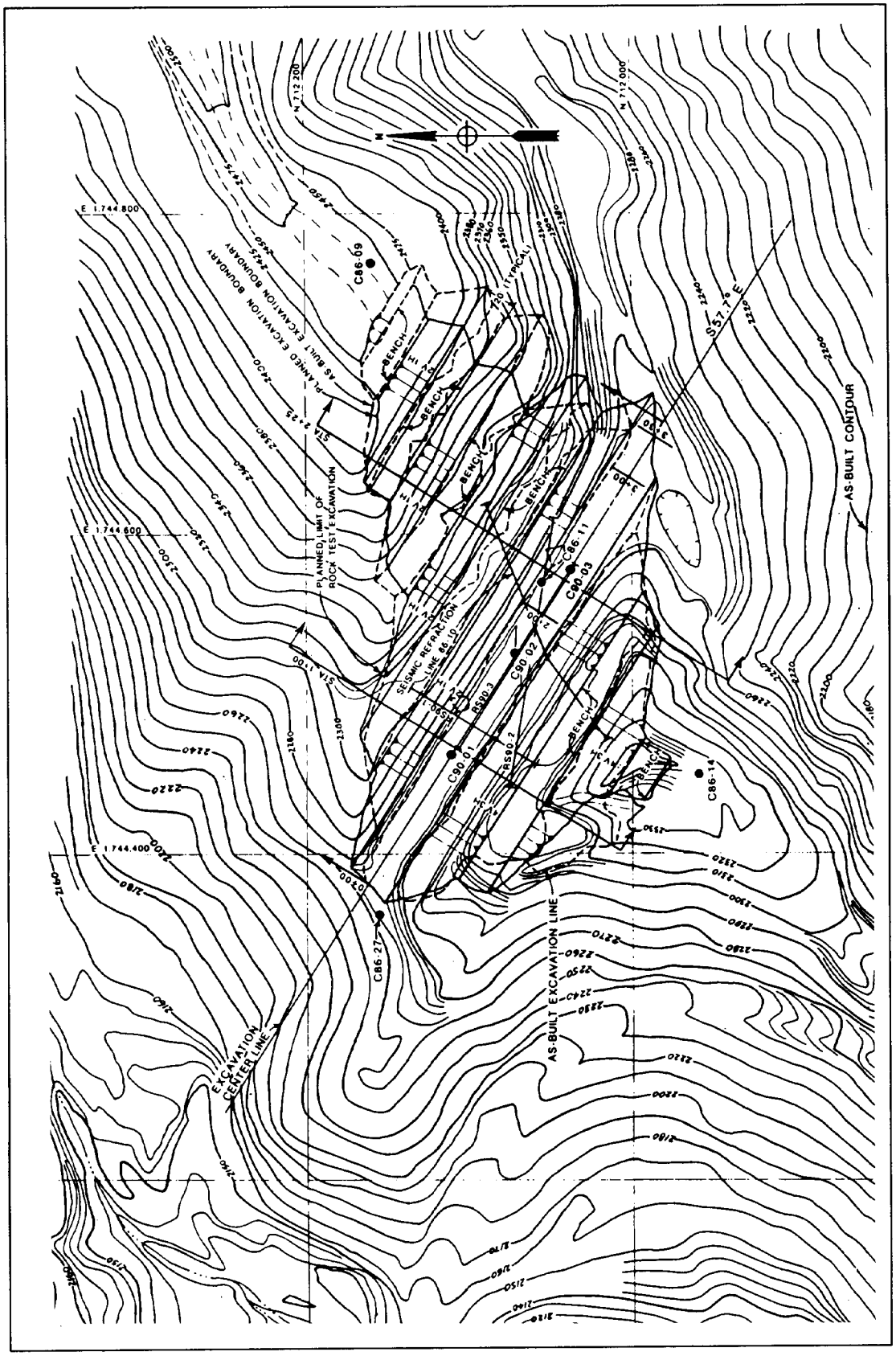


Figure 6-3. Example of a single test quarry layout showing bench and slope configurations, Seven Oaks Dam (after U.S. Army Engineer District, Los Angeles 1992)

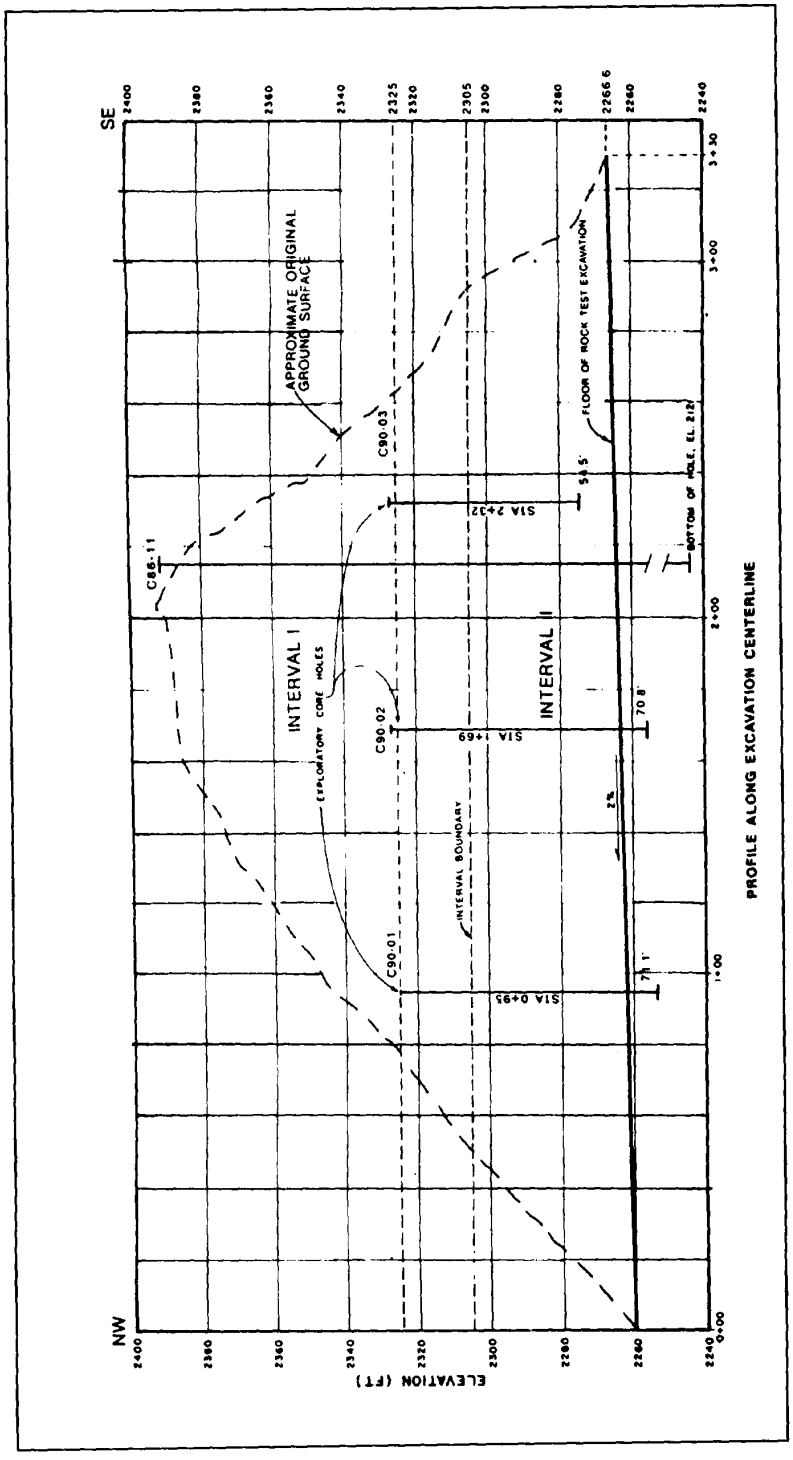


Figure 6-4. Profile along the excavation centerline of Figure 6-3

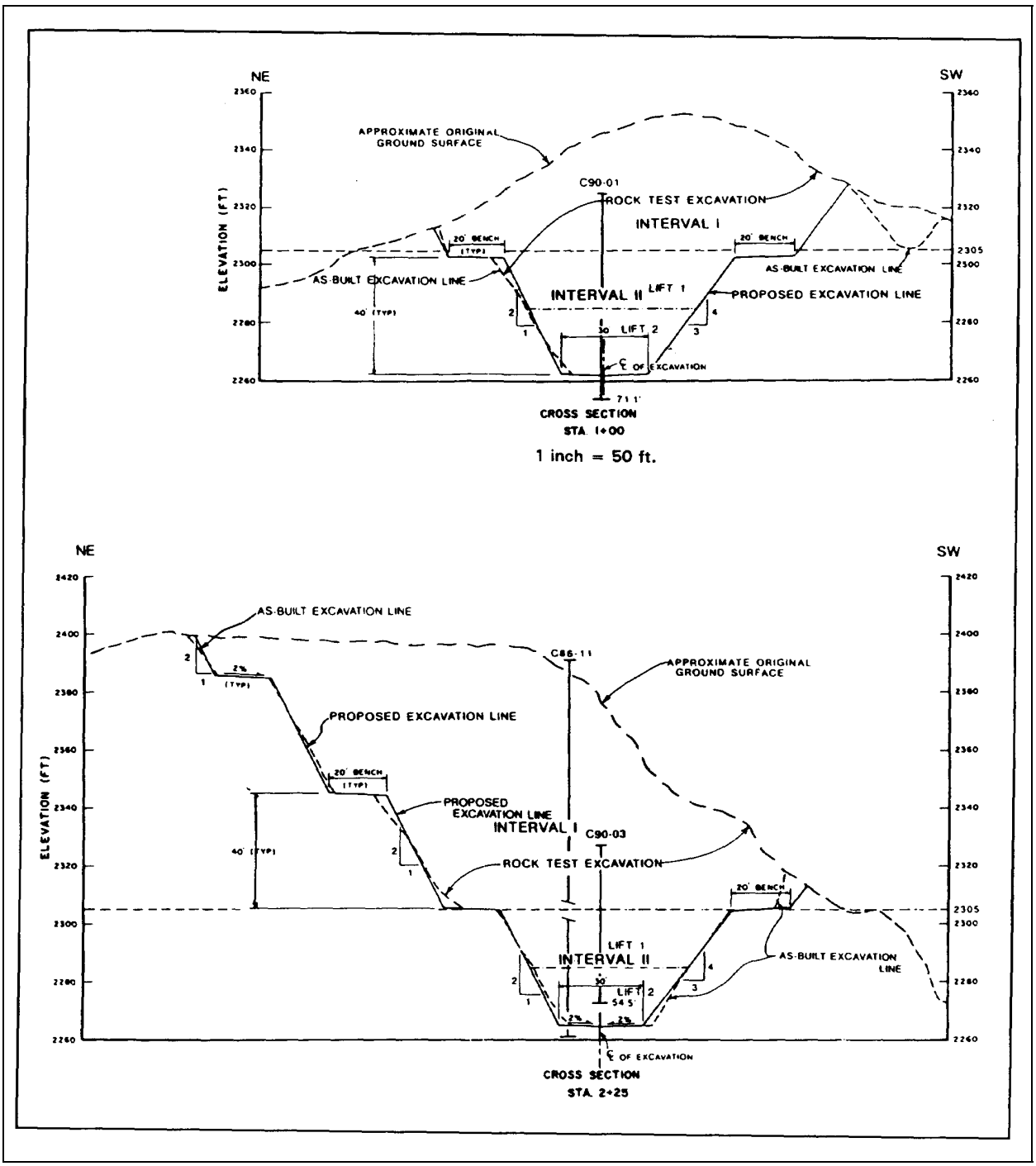


Figure 6-5. Additional sectional views of single quarry shown in Figure 6-3

several variations of the design should be tested in the quarry to prove and optimize the design. Bench design is based upon the overall slope stability analysis and upon the practicalities of excavation. The benches have the effect of flattening the overall slope and improving stability. They also provide added safety by catching some of the falling rock before it reaches the quarry floor. The benches can be sloped to control surface drainage and to provide haul road access to the quarry floor. Examples of slope and bench configurations are shown in Figures 6-3 through 6-5. Quarry bench height designs should be

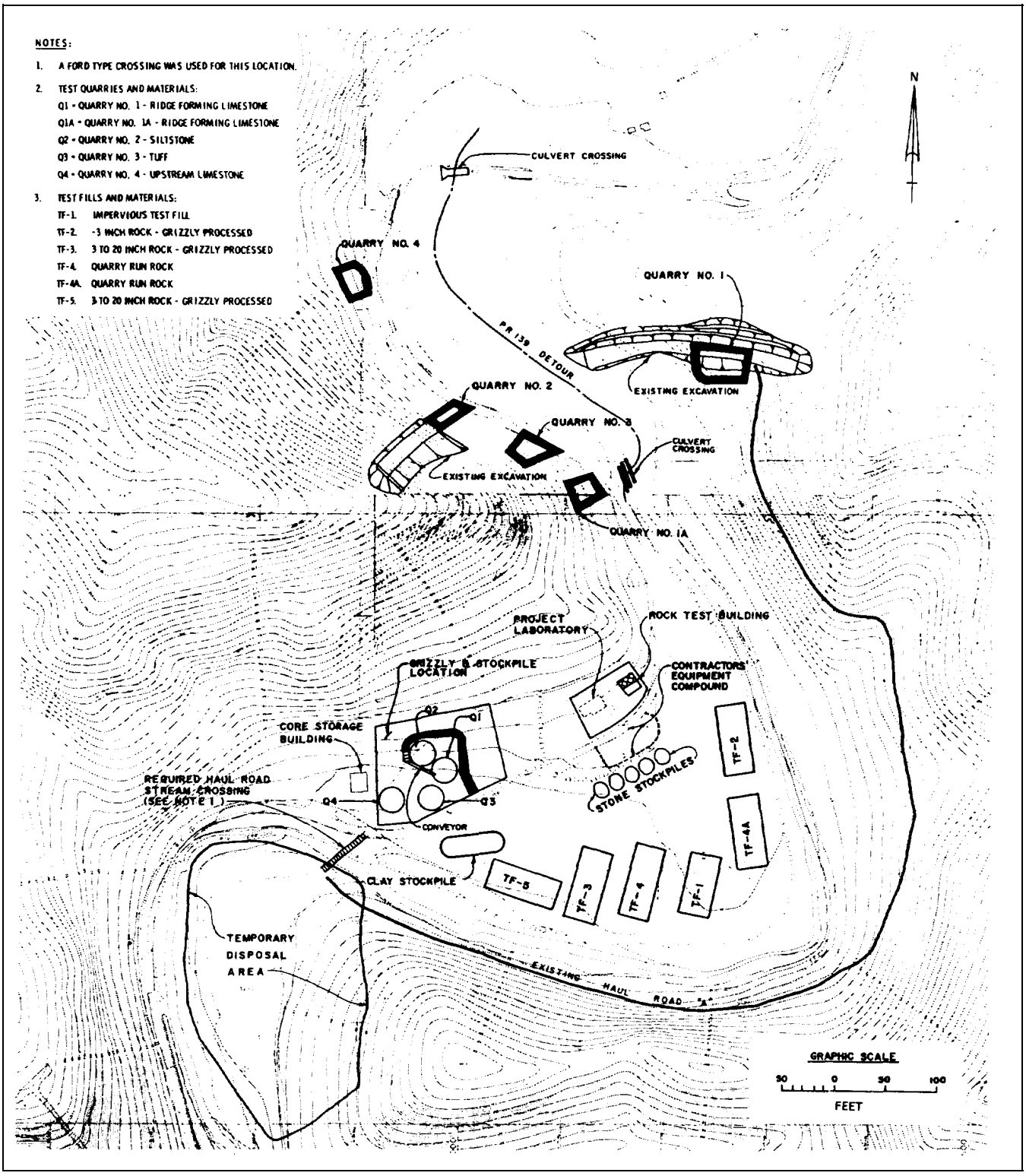


Figure 6-6. Example of a multiple test quarry layout where samples from several different rock strata are required for testing (after U.S. Army Engineer District, Jacksonville 1983)

based on anticipated excavation and hauling equipment and safety. Control of produced rock gradation is more a function of explosive type, quantity per hole, blast-hole spacing, decking of the charge, and burden than bench height. Where practicable, setting quarry benches coincident with slope berms will be efficient from a constructibility standpoint.

d. Presplitting patterns. The presplitting patterns developed during the design phase should be tested in the test quarry excavation. Variables in the design include hole spacing, hole size, stemming subdrilling, inclination, loading configuration, and charge weights. Hole spacing normally ranges from 46 to 91 cm (18 to 36 in.). The quality of the presplit slope normally decreases as the hole spacing increases, with 91 cm (36 in.) being about the maximum that will produce a satisfactory slope. It is important to maximize suitable spacing because this will reduce the number of presplit holes required and thereby reduce drilling costs. Good drilling alignment is very important to a satisfactory presplit slope cut. Alignment requires great care, particularly when drilling from rough or irregular surfaces. The techniques employed by the driller also affect the resulting alignment. It is important to specify great care in maintenance of alignment in the test quarry contract. It is also important to optimize the buffer zone between the presplit slope and the production blast lifts. Too large a buffer zone will keep the production blasts from pulling completely to the presplit slope and may result in incompletely broken rock. Too small a buffer zone will result in damage to the slope by the production blast. Variations of the combination of the above variables should be tested to determine which will work best under individual slope conditions. The basic designs should be furnished to the field with instructions that it will be modified as testing progresses and more is learned about the behavior of the rock mass. EM 1110-2-3800 provides detailed guidance on presplit design.

e. Production blasting patterns. There are numerous variables involved with blasting patterns which affect the particle size and gradation of the blasted rock pile. These variables and combinations thereof need to be investigated during the test quarry development to determine which combinations provide the most desirable rock fragmentation and gradation. Those variables that should be tested include: blast-hole diameter, hole spacing, powder factor, subdrilling depth, stemming type and length, type of explosive, loading configurations, decking, bench heights, firing delay patterns, and location of the free face (burden). It must be recognized that the characteristics of the rock mass impose limitations on the size of the produced particles. For instance, if rock joints occur on a repeating frequency of 30 cm (1 ft), it will not be possible to obtain significant quantities of rock with intermediate dimensions exceeding 30 cm (1 ft), no matter how the blasting pattern is designed. In other words, do not attempt a blast design to create fragmentation which is impractical to achieve. It is possible to achieve a gradation finer than the in situ gradation but not coarser. With this limitation understood, variations in the combinations of variables should be tested to develop those combinations which provide the most satisfactory rock mass fragmentation and gradation. The test quarry design should provide those patterns to be tested. The contract should provide for variations as more is learned from the initial tests. Figures 6-7 and 6-8 show examples of variations in test blasting patterns used to develop optimum patterns. EM 1110-2-3800 provides details on blast pattern design.

6-5. Gradation Measurements

There are no established standards or procedures specifically directed at making gradation determinations for blasted rock to be used in compacted rock fills. The new ASTM Designation D 5519-93 (ASTM 1994d) has become available (but not in time to be included in ASTM 1994a) for making gradation determinations for riprap and may be considered applicable. A complete discussion of gradation testing including ASTM 1994d is provided in Part II: Test Fills. The procedures used at the Corps of Engineers Carter's, Cerrillos, and Seven Oaks dam projects and described in the following paragraphs represent the typical sorts of past practices relative to obtaining gradations for rock materials upon which the ASTM standard.for riprap was based .

a. Carter's Dam. The gradation measurement procedure was to first carefully select a large representative sample from the blasted rock pile. The rock was then processed by hand over a series of inclined screens that separated the rock fragments into fractions of over 2.5 cm (1 in.), 7.6 cm (3 in.), 15.2 cm (6 in.), and 20.3 cm (8 in.). The minus 2.5-cm (1-in.) fraction was then processed with a Gilson® shaker using a normal nest of U.S. Standard Sieves (EM 1110-2-1906). The fragments from that fraction of the sample which were larger than 20.3 cm (8 in.) were individually passed through 30.5-cm (12-in.), 40.6-cm (16- in.), and 61-cm (24- in.) squares in order to determine the percent passing each of those sizes. It is necessary to obtain progressively larger representative samples for testing as the maximum particle size increases in order for the test results to be a satisfactory representation (estimation) of the blasted rock gradation. Figure 6-9 shows the configuration of the rock

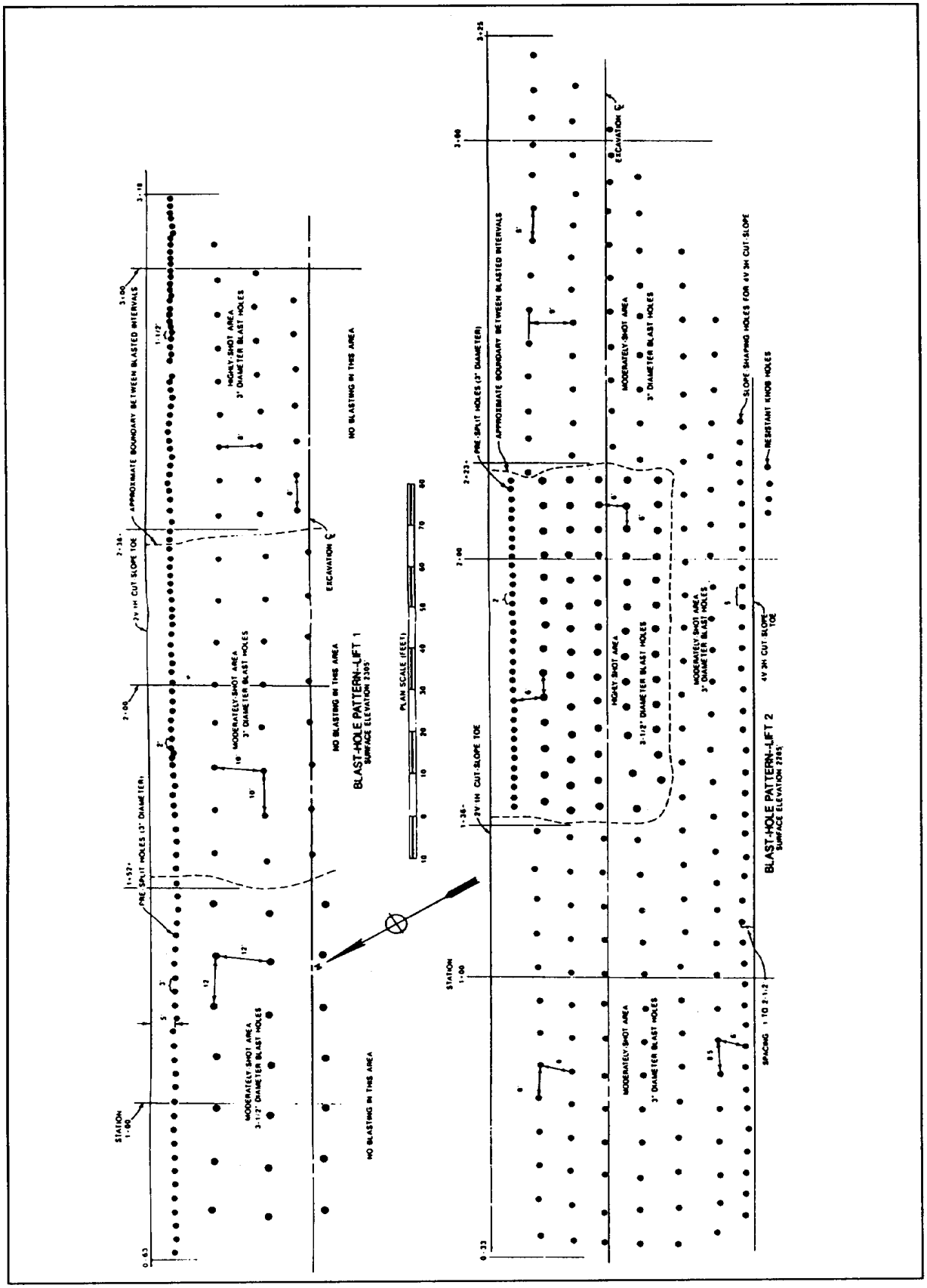


Figure 6-7. Example of variations in test blast patterns designed to develop the optimum production blast patterns (after U.S. Army Engineer District, Los Angeles 1992)

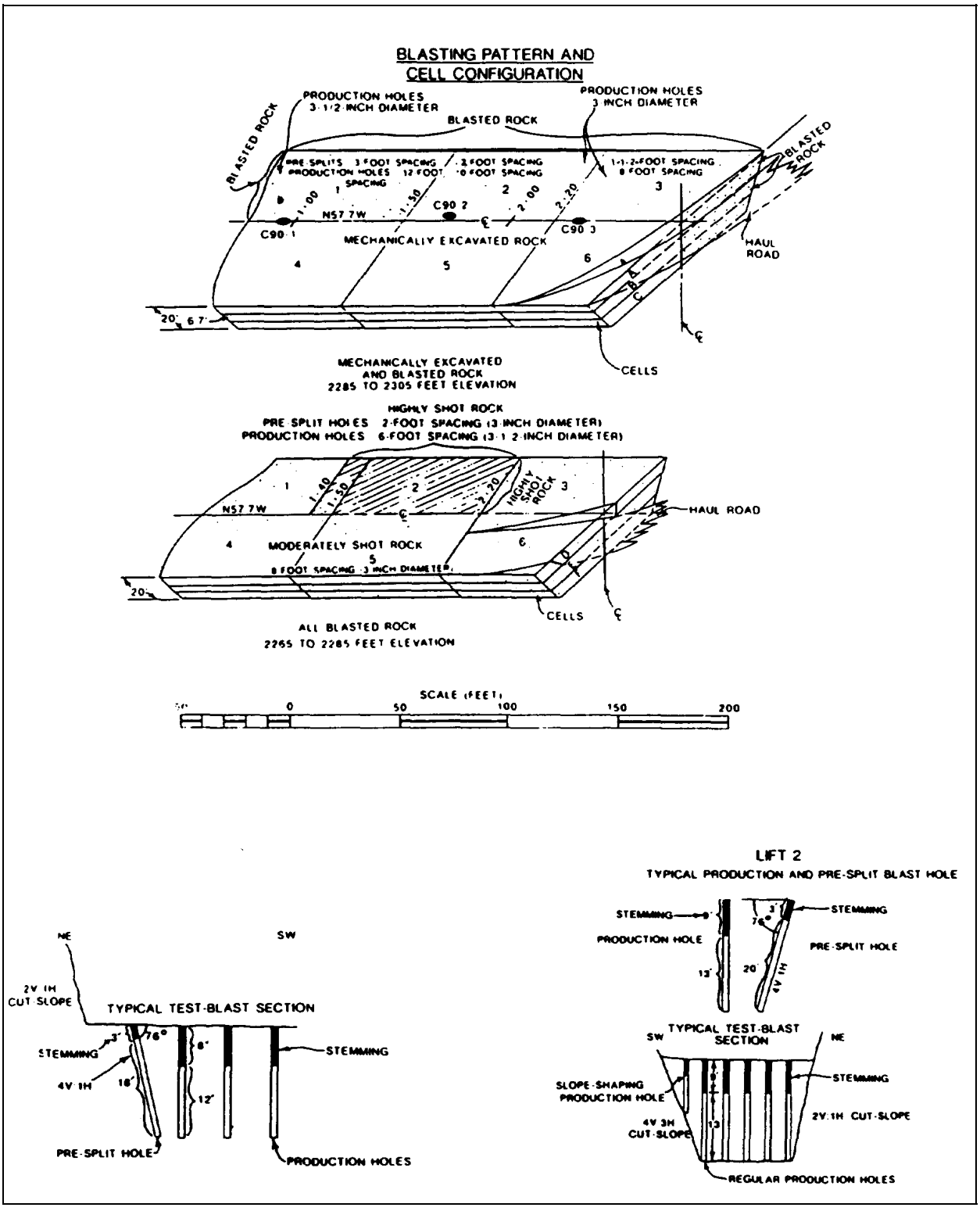


Figure 6-8. Additional information relative to Figure 6-7

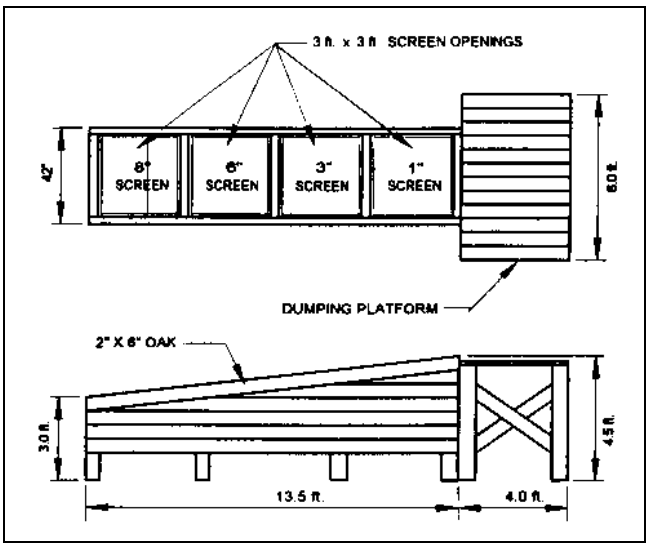


Figure 6-9. Example configuration of a rock gradation screening platform

gradation measurement platform used at Carter's Dam. The above information was obtained verbally from Mr. C. Colwell of the South Atlantic Division Laboratory (1993).

b. Cerrillos Dam. The gradation measurement procedure at Cerrillos Dam began with selection of a large sample weighing about 13.6 metric tons (30,000 lb). This sample was then split by the quartering method to obtain a sample weighing about 2.7 megagrams or metric tons (6,000 lb). The 2.7-metric ton (6,000-lb) sample was processed by hand over 15.2-cm (6-in.), 20.3-cm (8-in.), 22.9-cm (9-in.), 30.5-cm (12-in.), and 61-cm (24-in.) screens. The fraction passing the 15.2-cm (6-in.) screen was processed through a nest of screens using the Gilson® shaker. The gradation was based on the percent passing each screen size. This information was obtained verbally from Mr. P. Davila, U.S. Army Engineer Jacksonville District, Ponce (Puerto Rico) Resident Office (1993).

c. Seven Oaks Dam. Samples weighing approximately 4.5 metric tons (10,000 lb) were obtained and dumped on large sheets of plastic. These materials were sorted manually in the field using 7.6-cm (3-in.) opening Tyler screen and 15.2-cm (6-in.), 22.9-cm (9-in.), 30.5-cm (12-in.), and 45.7-cm (18-in.) sizing rings. The materials passing through the screen and sizing rings were placed in 2.1-cu m (55-gal) drums and weighed in the field on a platform scale. Individual rock fragments larger than 45.7 cm (18 in.) were measured in three diametrical directions and the weights estimated based on previously developed correlation charts. One drum of the minus 7.6-cm (3-in.) material from each sample was taken to the project laboratory for sieving and classification testing. This description was taken nearly verbatim from the U.S. Army Engineer District Los Angeles District Feature Design Memorandum (1992).

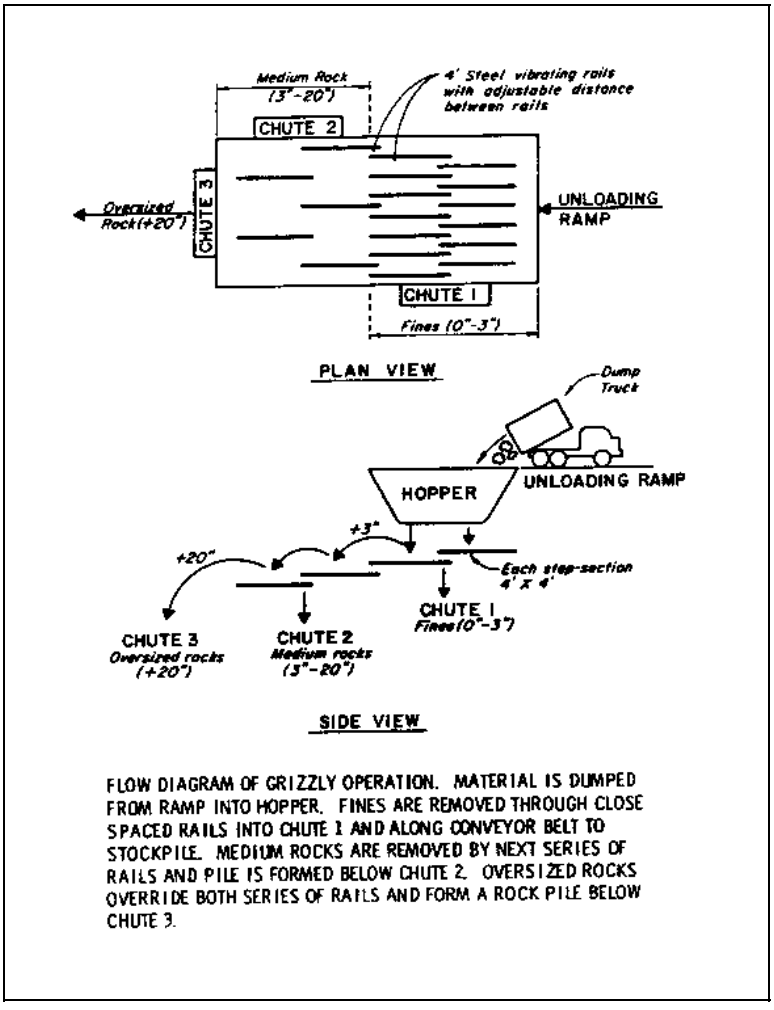
6-6. Deterioration and Incipient Fracture Examination

Some rock formations tend to deteriorate after excavation due to physical and/or chemical processes. This can have a very degrading effect on the rock products manufactured for various zones in a rock-fill dam and should be carefully evaluated during test-quarry and test-fill construction. Some conditions which lead to this type of deterioration are incipient fractures, bedding planes, abnormally high residual stresses, and chemically and/or physically unstable strata such as shale and volcanic ash or tuff. Some of this deterioration may occur in stock piles while some may occur due to the mechanical actions of loading, hauling, placement, and compaction into the fill. It is important to identify and assess degradation during the test-quarry and test-fill operation so that it can be dealt with during final design and construction. There are several approaches to determining whether or not this is a problem. Perhaps the simplest is to expose samples of rock core and blasted rock to the environment for a defined period of time and measure either changes in specimen size or weight loss. No changes would be an indication that degradation by chemical effects or weathering is not likely to occur in the rock fill. If changes do occur, then more sophisticated tests are needed to evaluate the magnitude of the problem. Petrographic analyses have provided an indication of breakdown due to incipient fracturing. Visual observations of individual blasted rock fragments are useful in determining the presence of incipient fractures or weak bedding planes. If there is an indication of either chemical or physical breakdown, it is desirable to obtain gradations of the blasted rock mass in the test quarry, then subsequently in the stock pile and ultimately in the test fills. These successive gradations will provide information on the degree of degradation which occurs. In some cases, it may be necessary to test repetitively in a stock pile to duplicate the times that a contractor is likely to stockpile materials. It is important to note that the mechanical action of repeatedly testing the same sample over a period of time may itself be a factor in any observed breakdown. This is discussed further in paragraph 7-6*b*. The blasting process often enlarges and expands incipient fractures and planes of weakness in intact rock blocks. This process will lead to degradation of the stone during project operation. The identification

of blast damage is very important. Both District and Division Laboratory geologic personnel should be involved in the evaluation of blast damage.

6-7. Rock Processing

Rock processing is frequently called for in the design of an earth-rockfill dam. This is particularly true for the manufacture of filter materials and materials to be placed in zones adjacent to filters. Where processing is anticipated, it is important to process the rock being produced in the test quarry for the test fills. The decision to process for the project situation should be carefully conceived and evaluated because rock processing, both in the test program and in the project construction, is very expensive. In other words, the fewer the zones of the dam that require processing, the less expensive the dam construction will be. The test fills should be constructed from rock materials that have the same characteristics as the project material is expected to have. In order to obtain this, some processing is likely to be required between the test quarry and the test fills. This may involve processing over a grizzly as diagrammed in Figure 6-10 or may require a portable crushing and screening plant to be brought to the site. Paragraph 7-7 provides further discussion of processing.



FLOW DIAGRAM OF GRIZZLY OPERATION. MATERIAL IS DUMPED FROM RAMP INTO HOPPER. FINES ARE REMOVED THROUGH CLOSE SPACED RAILS INTO CHUTE 1 AND ALONG CONVEYOR BELT TO STOCKPILE. MEDIUM ROCKS ARE REMOVED BY NEXT SERIES OF RAILS AND PILE IS FORMED BELOW CHUTE 2. OVERSIZED ROCKS OVERRIDE BOTH SERIES OF RAILS AND FORM A ROCK PILE BELOW CHUTE 3.

Figure 6-10. Flow diagram of a grizzly operation